

APPENDIX G

Evaluation of Monitored Natural Attenuation

EVALUATION OF MONITORED NATURAL ATTENUATION

Sauget Area 1 Remedial Investigation / Feasibility Study Sauget and Cahokia, Illinois

1.0 EXECUTIVE SUMMARY

As part of the Sauget Area 1 Feasibility Study (FS), monitored natural attenuation (MNA) is being considered as a remedial technology to address the groundwater plume emanating from Sites G, H, and I South. With the exception of Alternative 1 (No Action), MNA is a component of all remedial alternatives included in the Sauget Area 1 FS.

Implementation and evaluation of MNA is conducted using established protocols described in guidance documents (AFCEE, 1995; USEPA, 1998; USEPA 1999; USEPA 2004). Specifically, an evaluation of MNA typically includes collecting data to support one or more of the following primary lines of evidence:

- 1) Constituent concentration data showing plume stabilization and concentration reduction over time;
- 2) Geochemical conditions that are suitable for biodegradation and geochemical footprints that indicate biodegradation is actively occurring.
- 3) Microbiological data, from field or laboratory studies, supporting the occurrence of biodegradation.

In addition to these lines of evidence, analytical or computer models, calculations, or simulations can be used as needed to assess natural attenuation processes and predict cleanup times or concentrations at receptors.

In a technical memorandum dated October 7, 2008, USEPA provided guidance for documenting the MNA component in the Sauget Area 1 FS. In addition to identifying relevant protocols and directives, the technical memo listed a number of site-specific MNA evaluations that should be conducted for the FS.

This report provides a comprehensive site-specific evaluation of MNA, following the list of evaluations requested by the USEPA technical memorandum, to demonstrate that MNA processes will contribute to the achievement of cleanup objectives at Sauget Area 1. The summary table on the next page lists the requested evaluations and summarizes the responses developed in the following sections of this report.

Requested Evaluation	Summary of Response	
<i>Describe the key COCs and their primary natural attenuation mechanisms in groundwater, including retardation and biological degradation.</i>	Sorption is a relevant mechanism for most indicator constituents at the site, with retardation coefficients ranging between 1.2 and 6.6. Chlorobenzene and 1,4-dichlorobenzene, the key site constituents, are degraded biologically under both aerobic and anaerobic conditions. Rates are generally higher in aerobic conditions, leading to innocuous products (CO ₂).	Section 2
<i>Describe the groundwater geochemistry in terms of the natural attenuation parameters and how this supports the natural attenuation of the COCs.</i>	Geochemical data for Sauget Area 1 is limited. Available data suggest that anaerobic conditions are likely present near source areas. There are several positive geochemical indicators that anaerobic microbial activity is occurring in these areas.	Section 3
<i>Describe the amount of natural attenuation that has occurred for chlorobenzene and dichlorobenzenes.</i>	Mass flux calculations indicate that of the 2780 kg/yr of constituent mass leaving the Sauget Area 1 source areas in 2006, 2506 kg/yr of mass was removed from groundwater via natural attenuation processes.	Section 4
<i>For the COC mass flux that reaches the river area, discuss the percentage of the mass flux from Area 1 sites that is captured by the GMCS now and in the future.</i>	Groundwater modeling estimated that the GMCS captured 48% of the Sauget Area mass flux that reached the river area in 2006. The predicted percentages for 2010, 2020, 2030, and 2038 are 81%, 87%, 86%, and 86%, respectively.	Section 5
<i>For each alternative, discuss the estimated time for the groundwater to reach MCLs under MNA and whether this is reasonable compared to other methods such as P&T.</i>	Time to clean estimates for chlorobenzene in MHU, assuming only MNA, had a calculation result of 290 years. Estimates are at best +/- factor of 2, so range is on order of 150 to 580 years. Even with source mass reduction, it would still take hundreds of years to reach MCL for chlorobenzene.	Section 6
<i>Discuss the relative stability of the groundwater plume, whether it is expected to enlarge and whether it has adverse impacts on environmental receptors in the river.</i>	Groundwater modeling predicted an initial slight expansion of dilute constituent plumes due to shutdown of the highway dewatering system, but plumes would stabilize by 2020 and decline in subsequent years. The predicted mass flux to the river during this period is relatively small and represents no adverse impact to environmental receptors.	Section 7
<i>Describe the groundwater monitoring program and how it will be used to evaluate whether MNA is performing as expected.</i>	Monitoring well clusters will be installed along two transects. Quarterly monitoring data will be collected for two years to support MNA lines of evidence approach.	Section 8

2.0 KEY CONSTITUENTS AND PRIMARY ATTENUATION MECHANISMS

The following section contains a discussion of relevant attenuation processes for the key constituents of concern (COCs) at Sauget Area 1, which include chlorobenzene, 1,4-dichlorobenzene, benzene, tetrachloroethene, trichloroethene, cis-1,2-dichloroethene, vinyl chloride, 4-chloroaniline, and 2,4-D.

2.1 Natural Attenuation Processes

The fate and transport of an organic compound in groundwater is controlled by the compound's physical and chemical properties and the physical, chemical, and biological nature of the subsurface media through which the compound migrates. Several processes are known to cause a reduction in the concentration and/or mass of organic compounds dissolved in groundwater. Those processes that result in a change in a constituent's aqueous-phase concentration but not of the total mass in the system are termed nondestructive. Those processes that result in the reduction of constituent mass are referred to as destructive. Nondestructive processes include advection, hydrodynamic dispersion (mechanical dispersion and diffusion), sorption, dilution, and volatilization. Destructive processes include biodegradation and hydrolysis. Key processes active at Sauget Area 1 are advection, dispersion, sorption, and biodegradation. These four processes are discussed in more detail below.

Advection - Advection refers to the transport of solutes by the bulk movement of groundwater. Advection is the most important process driving the downgradient migration of aqueous-phase constituents in groundwater. The rate at which advective transport influences dissolved phase constituent migration is referred to as the seepage velocity. Seepage velocity is a key parameter in natural attenuation studies because it can be used to estimate constituent travel time.

Dispersion - Hydrodynamic dispersion is the process whereby a groundwater plume spreads out from the primary direction of groundwater flow. Dispersion results in reduced constituent concentrations as a result of mixing with groundwater cross gradient and downgradient of groundwater flow. Dispersion occurs as a result of two processes: mechanical dispersion and molecular diffusion. Mechanical dispersion is the dominant dispersion process at typical groundwater velocities. At very low groundwater velocities, molecular diffusion may become the dominant dispersion process. Molecular diffusion is generally ignored for most natural attenuation studies.

Dispersion is a function of groundwater seepage velocity and dispersivity occurs in the longitudinal, transverse, and vertical directions relative to groundwater flow. For most organic compounds, the amount of attenuation provided by dispersion is generally low compared to other attenuation processes such as sorption, biodegradation, and hydrolysis. The amount of attenuation resulting from dispersion is typically estimated using computer models such as BIOCHLOR (Aziz et al., 1999).

Sorption - Sorption is a non-destructive process in which organic compounds partition from groundwater and sorb to the aquifer matrix. Sorption of dissolved constituents onto the aquifer matrix results in slowing, or retardation, of the constituent relative to the groundwater seepage velocity and a reduction of aqueous phase concentrations.

The effect of sorption on the transport of organic compounds is represented by the retardation factor (R). The retardation factor quantifies two processes: 1) the degree to which a particular compound moves slower than the groundwater seepage velocity, and 2) the ratio of total constituent mass per volume of aquifer matrix to the volume of dissolved constituents. As shown in the following table, several of the indicator constituents for Sauget Area 1 have significant retardation factors.

Constituent	Soil-Water Distribution Coefficient, K_d (L/kg)	Retardation Factor, R (unitless)
Chlorobenzene	3.5×10^{-1}	3.0
1,4-Dichlorobenzene	9.9×10^{-1}	6.6
Benzene	9.4×10^{-2}	1.5
Tetrachloroethene	2.5×10^{-1}	2.4
Trichloroethene	2.7×10^{-1}	2.5
cis-1,2-DCE	5.7×10^{-2}	1.3
Vinyl Chloride	3.0×10^{-2}	1.2
4-Chloroaniline	1.1×10^{-1}	1.6
2,4-D	7.2×10^{-1}	5.1

Notes:

1. Retardation factor = $R = 1 + (\text{bulk density} \times K_{oc} \times f_{oc} / \text{porosity})$ where f_{oc} = fraction of organic carbon and K_{oc} = organic carbon distribution coefficient.
2. K_{oc} values for each constituent taken from TACO standard (35 IAC 742, Appendix C)
3. $f_{oc} = 0.0016$ based on (URS, 2004)
4. Bulk density = 1.7 g/mL and porosity = 0.3 based on typical values

Biodegradation - Biodegradation is a microbial-mediated destructive attenuation process. Transformation of an organic compound proceeds via one of two biochemical reaction pathways: 1) use of the compound as a primary growth substrate (i.e., electron donor or electron acceptor) or 2) co-metabolism. The use of the organic constituent as a primary growth substrate is the dominant mechanism resulting in degradation of constituents and occurs when microorganisms gain energy for growth by transferring electrons from an electron donor to an electron acceptor. Co-metabolism is typically less important under naturally occurring conditions (Wiedemeier et al., 1999) as co-metabolic biodegradation rates are much lower than growth-promoting pathways.

Depending on the geochemical characteristics of the hydrogeologic unit, organic compounds can either serve as the electron donor or the electron acceptor in microbial metabolism. Growth-promoting biological oxidation of organic compounds occurs when the microorganism uses the compound as an electron donor in a coupled oxidation-

reduction reaction. Biological oxidation may occur under both aerobic and anaerobic conditions. Many organic compounds can be used as electron donors in microbial metabolism, including petroleum-related hydrocarbons (e.g., BTEX), and the less oxidized chlorinated compounds such as dichloroethene (DCE), vinyl chloride, chlorobenzene, and the dichlorobenzene isomers. The most preferable electron acceptor utilized during biological oxidation of organic compounds is oxygen. Use of oxygen as an electron acceptor results in high energy yield for the microorganism; therefore, oxidation of organic compounds occurs relatively quickly in aerobic environments. Once oxygen has been depleted by aerobic bacteria, anaerobic consortia utilize alternate electron acceptors (e.g., nitrate, Fe(III), sulfate, carbon dioxide) during the oxidation of organic compounds.

Growth-promoting biological reduction of chlorinated organic compounds occurs when microorganisms utilize the chlorinated constituent as an electron acceptor during reductive dechlorination (or halorespiration). Reductive dechlorination occurs only under anaerobic conditions. The key electron donor in the reductive dechlorination process is hydrogen, which is produced during the fermentation of organic substrates, such as naturally-occurring organic matter or co-contaminants such as BTEX.

Compound-specific biodegradation processes are discussed below for each of the key COCs at Sauget Area 1.

2.2 Biodegradation of Chlorobenzenes

Chlorobenzenes can be degraded by a variety of both aerobic and anaerobic bacteria. Biodegradation generally proceeds faster aerobically (Wenderoth et al. 2003), and oxygen availability is a common rate-limiting factor for microbial-mediated chlorobenzene transformation.

Aerobic Biodegradation of Chlorobenzenes – Chlorobenzene and the dichlorobenzene (DCB) isomers, have been shown to be biodegradable under aerobic conditions. Several studies have shown that aerobic microorganisms utilize chlorobenzene (Reineke and Knackmuss, 1988; van der Meer et al., 1998; Rittman and McCarty, 2001) and the DCB isomers (Reineke and Knackmuss, 1988; van der Meer, 1991; Nielsen and Christensen, 1994; Rittman and McCarty, 2001) as growth-promoting substrates. These and other studies have further indicated the microorganisms capable of carrying out such degradation reactions are commonly encountered at contaminated sites.

The pathway for aerobic biodegradation of chlorobenzene is similar to that observed for BTEX degradation (van der Meer et al., 1998), and results in complete mineralization of chlorobenzene to chloride, carbon dioxide, and water. A similar pathway for the aerobic biodegradation of the DCB isomers has been proposed by van der Meer et al. (1991). Due to complete mineralization, the aerobic biodegradation of chlorobenzenes does not result in the production or accumulation of “daughter” products.

Anaerobic Biodegradation of Chlorobenzenes - Several reports have documented the anaerobic biodegradation of chlorobenzenes (e.g., Sims et al., 1991; Middeldorp et

al., 1997; Heidrich et al., 2004; Kaschl et al., 2005). There are two energy-yielding processes by which chlorinated compounds undergo anaerobic biodegradation: 1) reductive dechlorination and 2) direct oxidation (Wiedemeier et al., 1999). The specific degradation pathway depends on several factors including: i) the number of chlorine atoms on the molecule; ii) the geochemical conditions; and iii) the microbial consortia. In general, the more highly chlorinated compounds are only susceptible to reductive dechlorination, while the less chlorinated compounds are susceptible to both reductive dechlorination and direct anaerobic oxidation (U.S. EPA, 1998).

The reductive dechlorination pathway for chlorobenzenes proceeds via the sequential removal of a chlorine atom from the molecule. Reductive dechlorination of the DCB isomers to chlorobenzene has been well documented through both laboratory experiments (Ramanand et al., 1993; Nowak et al., 1996; Middeldorp et al., 1997) and in-situ field demonstrations (Heidrich et al., 2004). Further reduction of chlorobenzene to benzene has been suggested based on field and laboratory observations (Nowak et al., 1996; Kaschl et al., 2005), but isolation of microorganisms that carry out this reaction has not been documented.

Mineralization of chlorobenzene via direct anaerobic oxidation has also been suggested (Kaschl et al., 2005). This reaction, analogous to the direct anaerobic oxidation of vinyl chloride, likely proceeds via a pathway similar to that observed for anaerobic benzene oxidation. Similar to aerobic oxidation, direct anaerobic oxidation of chlorobenzene results in complete mineralization to chloride, carbon dioxide, and water without the production or accumulation of daughter products. The anaerobic oxidation of these compounds has been observed under a variety of geochemical conditions including nitrate-reducing, iron-reducing, sulfate-reducing, and methanogenic (Wiedemeier et al., 1999).

In general, anaerobic degradation of chlorobenzene proceeds slowly relative to anaerobic degradation of the DCB isomers. As a result, the chlorobenzene plumes tend to be more persistent than the DCB plumes at the Sauget sites.

2.3 Biodegradation of Chloroethenes

Chloroethenes include the compounds tetrachloroethene, trichloroethene, cis-1,2-DCE, trans-1,2-DCE, 1,1-dichloroethene (1,1-DCE) and vinyl chloride. Tetrachloroethene, trichloroethene, 1,2-DCE, and vinyl chloride are indicator constituents at Sauget Area 1. In anaerobic environments, the highly chlorinated solvents undergo reductive dechlorination in a process that is thermodynamically favorable because of the relatively high oxidation state of the carbon in these compounds (see reviews in Christ et al., 2005; Löffler and Edwards, 2006). The reaction involves the transfer of electrons to the chlorinated solvent compound coupled with the release of chloride, yielding lesser chlorinated metabolites. Consequently, reductive dechlorination is a stepwise process, with tetrachloroethene dechlorinated to trichloroethene, DCE (primarily the cis-1,2-DCE isomer), vinyl chloride, and finally to ethene. In general, each of these successive reactions occurs at a slower rate than the preceding step in the reaction.

In many cases, the microbes that mediate these reactions can use one or more of the chlorinated solvents as an electron acceptor in an energy-conserving process (halorespiration). In a subsurface setting, reductive dechlorination will occur once more favorable electron acceptors (i.e., oxygen, nitrate, iron/manganese, sulfate) are largely depleted, although reductive dechlorination often proceeds in conjunction with sulfate-reduction and methanogenesis, albeit at a slower rate. Stimulating dechlorination activity requires adequate concentrations of both the electron acceptor (the chlorinated solvent) and electron donor (typically a hydrogen-generating fermentable carbon compound). In some cases, DCE and vinyl chloride can accumulate because reductive dechlorination of these compounds requires more strongly reducing environments (relative to tetrachloroethene and trichloroethene). Alternate reaction pathways, including anaerobic oxidation of DCE and vinyl chloride to carbon dioxide, are known to exist but the contribution of these pathways to attenuation relative to reductive dechlorination is largely unknown.

Highly chlorinated solvents tend to be recalcitrant in aerobic environments because reductive dechlorination is not energetically favorable and dechlorinating microbes are inhibited by oxygen. However, oxidation of lesser chlorinated metabolites, including vinyl chloride and, to a lesser extent, DCE readily occurs as long as there is a co-substrate (e.g., methane, propane) present to stimulate aerobic organisms. Vinyl chloride is also known to serve as a primary substrate (electron donor) for a number of aerobic microbes. Trichloroethene tends to be slowly degraded in aerobic conditions, while tetrachloroethene is not known to oxidize in oxygen-rich groundwater. In all of these oxidation reactions, the end products are carbon dioxide, water, and chloride; organic intermediates formed during these reactions are generally extremely short-lived.

2.4 Biodegradation of Benzene

Benzene can be rapidly mineralized in aerobic conditions by a number of different types of indigenous microbes (Alvarez and Vogel, 1991; Borden et al., 1994). Using data from 26 lab and field studies of aerobic benzene degradation, Rifai and Suarez (1999) determined that the median half-life was approximately 3.5 days. It is generally accepted that this type of microbial metabolic capacity is widespread in nature. Therefore, significant benzene biodegradation activity (i.e., at levels which will affect the size of the plume) typically exists or can be stimulated (i.e., through addition of oxygen and/or nutrients) at a given site. Benzene can serve as a sole carbon and energy source during this oxidation reaction for a variety of organisms, though not all organisms that catalyze the reaction are capable of coupling it to a growth-supporting process. The metabolic strategy involves a succession of attacks by oxygenase enzymes to make the compound more susceptible to ring cleavage. This degradation results in complete mineralization to CO₂ and water, and accumulation of organic intermediates is generally not observed.

Benzene is also biodegradable in anaerobic environments (Bolt et al., 2002; Lovley, 2000; Johnson et al., 2003; Foght, 2008), such as iron-reducing (Anderson et al., 1998), sulfate-reducing (Lovley et al., 1995), nitrate-reducing (Burland and Edwards, 1999), and methanogenic conditions (Weiner and Lovley, 1998). Because depletion of all available

oxygen can occur rapidly following a release, the overall contribution of the anaerobic reactions to fuel hydrocarbon degradation is believed to be significant at some sites (Foght, 2008). However, the occurrence of anaerobic benzene degradation appears to be highly site-specific, with lag times prior to the initiation of degradation and/or inhibition when other fuel hydrocarbons are present. In general, reaction rates for anaerobic degradation are lower than those observed for aerobic biodegradation.

Benzene serves the same metabolic function (carbon and energy source) in both aerobic and anaerobic degradation, although different microbial populations are responsible in each case. Pathways for anaerobic biodegradation of benzene are still being elucidated (Foght, 2008), but the mineralization process yields the same products as those generated in aerobic respiration (CO₂, water, and biomass), along with the reduced species of the electron acceptor.

2.5 Biodegradation of 4-Chloroaniline

The degradation of 4-chloroaniline under both aerobic and anaerobic conditions has been reported (Bollag and Russel, 1976; Zeyer et al., 1985; Radianingtyas et al., 2003; McLaughlin et al., 2006; Vangnai and Petchkroh, 2007; Tongarun et al., 2008), although the relative reaction rates are not well documented. The majority of studies have focused on aerobic degradation using pure cultures or enrichments from soils where chloroaniline is present. In some cases, 4-chloroaniline has been shown to support growth of microbes that mediate the degradation reactions, while others rely on aniline as a growth substrate during degradation of 4-chloroaniline. Aerobic degradation of 4-chloroaniline has been observed to occur first by oxygenase attack to produce 4-chlorocatechol, followed by a meta-cleavage or modified ortho-cleavage pathway that eventually results in mineralization (i.e., CO₂). A recent study on reductive dechlorination of chlorinated anilines suggests that anaerobic degradation of 4-chloroaniline is limited (Tas et al., 2007).

2.6 Biodegradation of 2,4-D

2,4-dichlorophenoxyacetic acid (2,4-D) is an herbicide that is readily biodegradable in aerobic conditions (Estrella et al., 1992; Ka et al., 1994). During this degradation process, it can serve as a sole carbon and energy source for a variety of organisms (Ka et al., 1994). While 2,4-D degradation activity appears to be widespread and has been observed in soils with no history of 2,4-D exposure (Kamagata et al., 1997), a lag time has been observed before the onset of degradation, presumably following growth of a suitable microbial population. The degradation pathway generally proceeds through removal of the phenoxy group and possibly one of the chloride ions, followed by oxygenase and hydroxylase mediated reactions to make the compound more susceptible to ring cleavage (Kitagawa et al., 2002). This degradation results in complete mineralization to CO₂, and accumulation of intermediates has not been widely reported. Anaerobic degradation of 2,4-D has not been extensively studied, but reductive dechlorination to 4-chlorophenol is known to occur in anaerobic conditions (Mikesell and Boyd, 1985), and anaerobic mineralization of this compound is well documented (Haggeblom and Young, 1995).

3.0 GROUNDWATER GEOCHEMISTRY

3.1 Overview of Sauget Area 1 Geochemical Conditions

In 2005-2006, URS conducted groundwater sampling and testing for COCs and geochemical parameters at selected wells throughout the region, including Sauget Area 2, Sauget Area 1, the Solutia Krummrich facility, and the Conoco Phillips property. The data from this sampling program were documented in the Sauget Area 2 Remedial Investigation report (URS, 2009).

Attached with this memorandum are well location maps and a table of geochemical parameter data for wells at and downgradient of Sauget Area 1. The range of geochemical parameter values measured in the Shallow Hydrogeologic Unit (SHU), Middle Hydrogeologic Unit (MHU), and Deep Hydrogeologic Unit (DHU) are summarized below:

Geochemical Parameter Values Measured at and Downgradient of Sauget Area 1			
Parameter	SHU	MHU	DHU
O ₂	0.65 – 4.44 mg/L	0.37 – 1.591 mg/L	0.21 – 6.56 mg/L
Nitrate	< 0.05 – 2.8 mg/L	< 0.05 – 1.8 mg/L	< 0.05
Manganese	0.023 – 4.1 mg/L	0.15 – 2.7 mg/L	0.16 – 0.62 mg/L
Iron	NA	NA	NA
Sulfate	29 – 240 mg/L	< 5 – 200 mg/L	< 5 – 61 mg/L
Methane	ND – 5.4 mg/L	0.00019 – 2.8 mg/L	0.15 – 0.79 mg/L
CO ₂	15 – 440 mg/L	33 – 260 mg/L	15 – 81 mg/L
ORP	-18 – +124 mV	-76 – +98 mV	-133 – +10 mV
Alkalinity	230 – 820 mg/L	340 – 710 mg/L	490 – 620 mg/L
TOC	< 1 – 780 mg/L	< 1 – 41 mg/L	2.2 – 9.1 mg/L
Chloride	3 – 250 mg/L	11 – 350 mg/L	50 – 190 mg/L

Notes:

1. NA = not available/not analyzed; ORP = oxidation-reduction potential; TOC = total organic carbon.

These data were compiled from a subset of wells that fall into the following categories based on location.

- Background/upgradient: These wells, which include IMW-1D, IMW-1I, IMW-1S, are screened in different hydrogeologic units and are clustered in a single location upgradient of Site I North.
- Monitoring wells surrounding the TSCA cell: These wells, which include TCMW-1S, TCMW-1M, TCMW-2, TCMW-3S, TCMW-3M, TCMW-4, TCMW-5S, TCMW-5M, TCMW-6S, TCMW-6M, are located cross gradient to Sauget Area 1 and are not representative of Sauget Area 1 source or plume areas.
- Sauget Area 1 source area wells: These wells, which include EE-01, EE-03, and EEG-107, are located within either Site H or Site G.
- Downgradient wells: These wells, which include GM-18A, GM-18B, GM-31A, GM-31B, GM-31C, are located within the Sauget Area 1 plume in the area

downgradient of the Sauget Area 1 source areas. However, the W.G. Krummrich plume may also influence this downgradient area.

An assessment of geochemical conditions was performed using the approach outlined by Truex et al. (2006) by determining if the above parameters meet general criteria for aerobic or anaerobic conditions. The available data on Table 1 indicate that the geochemical conditions at the site are slightly anaerobic (reducing) within Sauget Area 1 and immediately upgradient of the site, and aerobic (oxidizing) in the downgradient plume. This is based primarily on ORP and O₂ values, which are limited for Sauget Area 1 and do not appear necessarily correlated for this dataset. Note that the apparent reducing conditions present in the upgradient area (near well IMW-1D, IMW-1M, IMW-1S) is not consistent with the more oxidizing conditions that are encountered in areas side-gradient of the Sauget Area 1, Sauget Area 2, and W.G. Krummrich sites, particularly closer to the river.

With respect to other geochemical indicators shown on Table 1, nitrate and nitrite concentrations are generally very low in all wells, suggesting anaerobic conditions predominate. Sulfate concentrations are generally higher in the wells located closer to source areas (e.g., EE-01, EE-03, EEG-107) even though these areas meet most other anaerobic indicator criteria. For example, this same set of wells in the source areas also contains relatively high levels of total organic carbon and methane, both of which are indicative of anaerobic conditions. Therefore, the preponderance of data suggests that anaerobic conditions exist within the source areas.

3.2 Geochemical Conditions Favoring Biodegradation of Chlorobenzenes and Other Site Constituents

As described in Section 2.2, chlorobenzenes are degraded under both aerobic and anaerobic conditions. For the aerobic biodegradation of chlorobenzenes, the most important geochemical condition is the presence of dissolved oxygen. The presence of abundant amounts of electron donor, such as within a contaminant plume, often leads to the rapid depletion of dissolved oxygen. Based on available geochemical data listed in Table 1, aerobic degradation pathways are more relevant at the plume boundaries (e.g., near GM-18, GM-31) where slightly to moderately higher levels of dissolved oxygen have been measured.

Under anaerobic conditions, there two pathways for the biodegradation of chlorobenzene and DCB isomers: reductive dechlorination and direct oxidation. Reductive dechlorination predominantly occurs under sulfate-reducing or methanogenic conditions, once other electron acceptors (i.e., oxygen, nitrate, and Fe(III)) have been depleted. Reductive dechlorination has also been observed under nitrate-reducing and iron-reducing conditions, but reaction rates are typically lower. Therefore geochemical conditions indicative of reductive dechlorination include:

- low dissolved oxygen concentrations,
- low nitrate concentrations,
- low sulfate concentrations,

- elevated Fe(II) concentrations,
- elevated methane concentrations, and
- elevated chloride concentrations.

Based on available geochemical data (Table 1), anaerobic degradation pathways are most relevant in the source areas at Sauget Area 1 (e.g., near EE-01, EE-03, and EEG-107), where the majority of these anaerobic indicator criteria are largely met.

Note that anaerobic conditions are generally more favorable for degradation of the more highly chlorinated ethenes (e.g., PCE), while aerobic conditions promote more rapid degradation of the less chlorinated ethenes and benzene.

3.3 Temporal and Spatial Trends in Geochemical Parameters

There is insufficient data in this limited dataset to establish temporal patterns in the geochemical parameters. Consequently, it is difficult to determine whether depletion of electron acceptors is occurring, either as a process that competes with reductive dechlorination of chlorobenzenes or as a process that supports the direct oxidation pathway.

Similarly, there are few spatial patterns that are apparent from an evaluation of the existing data, as would be indicated by depletion or enrichment of certain parameters along the direction of groundwater flow. A notable exception is the Site G source area in the SHU. Based on data from a single monitoring well located within the Site G boundary (EEG-107), groundwater is significantly more reduced compared to other Sauget Area 1 wells that were sampled, with higher levels of methane as well other indicators of anaerobic activity (e.g., chloride, total organic carbon, carbon dioxide). This is likely attributable to historic release of organic compounds that stimulated microbial activity, depleting available oxygen and establishing largely anaerobic conditions.

3.4 Endproduct Formation

There is limited evidence of product formation from biological attenuation of site constituents. For example, ethene and ethane were detected in a single well in the SHU (EEG-107, located in Site G) at concentrations of 8.8 µg/L and 17 µg/L, respectively, out of the set monitoring wells sampled during 2005 in Sauget Area 1. Similarly, low levels of ethene (1.5 µg/L) and ethane (1.5 µg/L) were detected in a single well in the MHU (EE-01), and ethane (15 µg/L) was detected in a single well in the DHU (GM-31C). Both of these wells are located within or downgradient of Site H. Ethene and ethane are endproducts of the reductive dechlorination pathway for chlorinated ethanes and are considered positive indicators of biological natural attenuation capacity.

Other potential attenuation pathways for the various indicator constituents yield products that are not measurable using standard methods. For example, complete oxidation of any of the constituents results in CO₂ as an endproduct, but increases in this compound are difficult to discern relative to background CO₂ concentrations. Again, the exception was in Site G, where the measured CO₂ concentration (440 mg/L) appears to be higher

than the concentration range in the wells located outside of this source area (15 – 260 mg/L). The elevated level of CO₂ is consistent with the detections of ethene and ethane in this same well, indicating that anaerobic attenuation of groundwater constituents has occurred.

Chloride is released during both the aerobic and anaerobic biodegradation of chlorobenzene, DCB isomers, and chlorinated ethenes. Chloride concentrations in the source areas are relatively high when compared to downgradient wells. However, the background chloride concentration in each of the Sauget Area 1 hydrogeologic units is not well-established based on the available data. This makes it difficult to determine if chloride concentrations in the Sauget Area 1 source areas or plumes are elevated due to attenuation of site constituents.

4.0 EXTENT OF CHLOROBENZENE AND DICHLOROBENZENE ATTENUATION

An evaluation of the attenuation of groundwater constituents is discussed in Section 6.5 of the Sauget Area 1 RI report (GSI, 2012b). This evaluation compared the mass flux leaving the Sauget Area 1 source area (calculated based on groundwater concentrations measured in source area wells multiplied by the groundwater flow rate) to the modeled mass flux that arrived was removed by the GMCS and the modeled mass flux that arrived at the river (estimated using the updated regional groundwater fate and transport model, GSI, 2012a).

Mass Fluxes for Sauget Area 1 Plumes

	Mass Flux (kg/yr)	Estimation Method
Estimated Mass Flux from Source Area	2780	Mass flux study at Site I (GSI, 2005)
Modeled Mass Flux Removed by GMCS in 2006	142	Groundwater modeling (GSI, 2008)
Modeled Mass Flux to River in 2006 with GMCS On	94	Groundwater modeling (GSI, 2008)
Estimated Mass Flux Removed by Natural Attenuation	2554	Mass balance (2780–142–94=2554)

Using this mass flux approach, it was demonstrated that an estimated 2554 kg/yr of mass from Sauget Area 1 sources was removed from groundwater via natural attenuation processes in 2006. This calculation indicates that extensive attenuation of mass occurs during groundwater transport prior to reaching the river.

Data for other indicators of biodegradation-based attenuation, such as chloride, do not provide sufficient resolution for evaluating the amount of attenuation that is currently occurring. For example, the chloride concentration in wells screened in the MHU in Sauget Area 1 varies widely, from less than 10 mg/L to greater than 400 mg/L, a range similar to that measured in wells located downgradient of Sauget Area 1 (see Table 1 and Figure 8-5). While it is unclear whether this range falls outside of the background

chloride concentration range, it is certainly significantly higher than the total chlorinated VOC (CVOC) concentrations measured in any of the hydrogeologic units beneath the source areas. Because all of the COCs present at Sauget Area 1 release less than 1 mg of chloride per mg of CVOC degraded, it is not possible to distinguish between the chloride mass contributed by biodegradation processes and background chloride concentrations.

5.0 MASS FLUX CAPTURED AT RIVER

The updated regional groundwater model report (GSI, 2012a) included an evaluation of mass flux captured by the GMCS. For Sauget Area 1 sources only, overall, when all modeled COCs are included, 60% of the total plume mass flux that would have discharged to the river in 2006 without the GMCS is predicted to be captured by the GMCS. The percentages predicted to be captured in 2010, 2020, 2030, and 2038 are 65%, 73%, 73%, and 73%, respectively. Consequently, a large majority of the mass from Sauget Area 1 sources that is not attenuated between the source area and the river will be captured by the GMCS.

6.0 TIME TO REACH MAXIMUM CONTAMINANT LEVELS

The regional groundwater flow and transport model was used to develop time to clean estimates for chlorobenzene and 1,4-dichlorobenzene in the MHU and DHU at a hypothetical monitoring location approximately halfway between the Sauget Area 1 sources and the Mississippi River. The hypothetical monitoring location was approximately 2300 ft downgradient of Site I South. Time to clean (i.e., time to reach the MCL) was estimated for four scenarios: i) MNA alone; ii) 50% source mass reduction in 2010 plus MNA; iii) 75% source mass reduction in 2010 plus MNA; iv) 90% source mass reduction in 2010 plus MNA. Results are documented in a technical memorandum (GSI, 2009c).

There is considerable uncertainty in the time to clean estimates, and the calculated estimates are probably accurate to within a factor plus or minus of 2 at best. As indicated on the table below, even with source mass reduction in 2015, it will still likely take on the order of hundreds of years to reach the MCL for chlorobenzene.

Time to Clean Estimates for Chlorobenzene in MHU
at Hypothetical Monitoring Location 2300 ft Downgradient of Site I South

Case	Calculated Result (years from 2015)	Estimated Range (years from 2015)
MNA only	290	150-580
50% source mass removal plus MNA	250	130-500
75% source mass removal plus MNA	220	110-440
90% source mass removal plus MNA	160	80-320

1) Estimates are rounded to nearest ten years.

7.0 PLUME STABILITY

The stability of the constituent plumes at Sauget Area 1 can be evaluated based on the results of the regional groundwater fate and transport model (GSI, 2008) and the updated groundwater model (GSI, 2012a). The regional model was calibrated for the following seven indicator constituents for Sauget Area 1: chlorobenzene, 1,4-dichlorobenzene, tetrachloroethene, trichloroethene, cis-1,2-DCE, vinyl chloride, and 2,4-D. Benzene and 4-chloroaniline are the two Sauget Area 1 indicator constituents that were not included in the model calibration.

A series of modeled isoconcentration contour maps for the seven calibrated constituents, with separate maps for each constituent for the SHU, MHU, and DHU, were generated using the flow and transport model. Each figure includes a map showing the modeled isoconcentration contours for 2006 and predicted isoconcentration contours for 2038. See Figures 6-1 through 6-42 of the Sauget Area 1 RI report (GSI, 2012b).

Modeling results established that:

- Chlorobenzene and 1,4-dichlorobenzene plume cores, located in the MHU and DHU west of Sauget Area 1 onto Lot F, are relatively stable between 2006 and 2038.
- Slight downgradient expansion of the dilute portion (0.1 mg/L or less) of several of the constituent plumes is observed during this same period, including tetrachloroethene, trichloroethene, cis-1,2-DCE, and vinyl chloride. The plume cores for these four constituents are centered around Site G, and no expansion of these areas is observed due to source attenuation during this period.
- A very small plume of 2,4-D is present in the SHU in the immediate vicinity of Site G in 2006 that persists to 2038; no plume of 2,4-D in the MHU or DHU.

The mass flux data generated by the groundwater model for the period between 2006 and 2038 shows that the modeled mass flux to the River will decrease steadily due to natural attenuation and will continue to decrease as the source is depleted.

Modeled Mass Flux To River from Sauget Area 1 Plumes with GMCS ON

Year	All 7 COCs (kg/yr)	2,4-D (kg/yr)	CB (kg/yr)	1,2-DCE (kg/yr)	1,4-DCB (kg/yr)	VC (kg/yr)	TCE (kg/yr)	PCE (kg/yr)
2006	94	0	37	8	3	46	0	0
2010	72	0	30	6	2	34	0.06	0.009
2020	62	0	26	6	2	27	0.2	0.02
2030	55	0	23	6	2	24	0.2	0.01
2038	50	0	21	5	2	22	0.2	0.01

CB = chlorobenzene; DCB = 1,4-dichlorobenzene; 2,4-D = 2,4-Dichlorophenoxyacetic acid; PCE = tetrachloroethene; TCE = trichloroethene; 1,2-DCE = cis-1,2-Dichloroethene; VC = vinyl chloride; kg/yr = kilograms per year.

The data above represent the predicted mass flux that will reach the river with the GMCS on. Because containment and natural attenuation mechanisms do not result in net zero flux to the river, potential adverse effects on environmental receptors in the river must be assessed, particularly since the model predicts a temporary expansion of dilute portions of the groundwater plumes for several of the constituents.

To assess groundwater concentrations along the River over time, point of compliance (POC) wells will be located along the River north of the barrier wall to monitor the plumes from Sauget Area 1. The locations for the POC wells can be determined during the remedial design phase. Conceptually, monitoring wells BSA-MW-5D and CPA-MW-5D could be suitable locations for POC wells for Sauget Area 1 (see Figure 10-5 of the FS report).

8.0 GROUNDWATER MONITORING PROGRAM

The MNA component of the Sauget Area 1 FS includes a monitoring program to quantitatively demonstrate the effectiveness of MNA for addressing the Sauget Area 1 plumes. In order to gather data to support the lines of evidence approach, a network of groundwater monitoring wells would be installed at key locations throughout the plume. The monitoring network would be sampled quarterly for a period of two years in order to establish constituent concentration trends, geochemical conditions, and sustainability of MNA as a long-term remedy.

The conceptual monitoring network, sampling and testing plan, and data analysis methods for the MNA demonstration study are discussed in more detail below.

8.1 Proposed Monitoring Network

8.1.1 Monitoring Well Locations

The conceptual MNA monitoring network includes a total of thirteen well clusters installed along two groundwater flow paths from Sauget Area 1 source areas downgradient toward the Mississippi River (see Figure 13-1 from the RI/FS report). The network includes a transect consisting of five well clusters located upgradient and downgradient of Site I South and a transect consisting of eight well clusters located upgradient and downgradient of Sites G or H.

For these two transects, the farthest upgradient wells are located outside of the general source areas for Sauget Area 1. These two upgradient well clusters will provide baseline characterization data for assessing distribution of COCs, geochemical parameters, and microbial parameters to support the MNA evaluation.

In addition to the conceptual monitoring well network shown on Figure 13-1, other existing wells within or downgradient of the Sauget Area 1 source areas may be included

as part of the MNA monitoring program in the future, if needed, based on evaluation of groundwater monitoring data from the conceptual MNA monitoring well network.

In addition, as discussed in the previous section, there will need to be POC wells located along the Mississippi River north of the barrier wall at Sauget Area 2 Site R to monitor the plumes from Sauget Area 1. The locations for the POC wells can be determined during the remedial design phase. Conceptually, monitoring wells BSA-MW-5D and CPA-MW-5D could be suitable locations for POC wells for Sauget Area 1 (see Figure 10-5 of the FS report).

8.1.2 Monitoring Well Screen Intervals

Monitoring well clusters at locations 1 through 8 will include one monitoring well screened within the SHU, one monitoring well screened within the MHU, and one monitoring well screened within the DHU. Monitoring well clusters in downgradient areas at locations 9 through 13 will include wells screened only in the MHU and DHU because wells in the SHU are not needed in those downgradient areas.

8.2 Groundwater Sampling and Testing Plan

8.2.1 Monitoring Frequency

The monitoring network would be sampled quarterly for a period of two years in order to establish constituent concentration trends, geochemical conditions, and sustainability of MNA as a long-term remedy. The monitoring program would be evaluated after two years and the sampling frequency would be decreased to semiannual or annual sampling, as appropriate.

8.2.2 Monitoring Parameters

A comprehensive set of monitoring parameters (see table below) will be included in the sampling plan for Sauget Area 1, consistent with guidance documents on appropriate MNA evaluations (AFCEE, 1995; USEPA, 1998; USEPA 1999; USEPA 2004). Static water level monitoring of an expanded number of MHU and DHU wells will be performed, following the same monitoring frequency described above.

At a select number of wells, microbe and population-specific genetic assays could be performed to provide data for the demonstration of the third line of evidence. Bio-Trap samplers would be deployed in several wells located within the source area and plume core and in a background well outside of these areas for 30 to 60 days. The samplers would be analyzed by a commercial laboratory that specializes in the application of molecular biological tools for environmental investigations (e.g., Microbial Insights). Nucleic acid-based, quantitative assays (qPCR) would be employed to establish that suitable microbial populations exist at Sauget Area 1. If necessary, these assays could be performed on a regular basis (e.g., annually) during implementation of MNA.

Monitoring Parameters for MNA Groundwater Monitoring Program

Constituent	Method	Data Use ¹	Interpretation ¹
Constituents of Concern			
Chlorobenzene 1,4-Dichlorobenzene Benzene Tetrachloroethene Trichloroethene cis-1,2-Dichloroethene Vinyl chloride	8260B	Primary COC and/or daughter product, evaluate trends over time and distance	Stable or decreasing trends support MNA
4-Chloroaniline	8270C	Primary COC, evaluate trends over time and distance	Stable or decreasing trends support MNA
Geochemical Parameters			
Alkalinity	310	Measure buffering capacity of groundwater	Elevated levels indicate stable pH
Carbon dioxide	4500	Final product of organic carbon mineralization	Elevated levels indicate mineralization
Chloride	9056	Final product of MCB/DCB mineralization	Elevated levels indicate mineralization of CBs and other COCs
Iron II (dissolved)	3500	Indicator of anaerobic biological activity	Elevated levels indicate reduction of Fe(III)
Methane/Ethane/Ethene	SW3810 Modified	Indicator of anaerobic biological activity	Elevated levels indicate strong anaerobic conditions
Nitrate	9056	Indicator of anaerobic biological activity	Low concentrations indicate nitrate reduction
Oxidation-Reduction Potential (ORP)	Field meter	Indicator of oxidizing or reducing nature of groundwater	Values < 50mV indicate anaerobic conditions
Oxygen	Field meter	Indicator of aerobic biological activity	Values < 1 mg/L indicate anaerobic conditions
pH	Field meter	Verify pH within range of biological activity	Values between 5 and 9 are optimal
Sulfate	9056	Indicator of anaerobic biological activity	Low concentrations indicate sulfate reduction
Total Organic Carbon	9060	Determine the abundance of electron donor	Elevated levels indicate available source of carbon
Microbial Parameters			
Microbial counts	Bio-Trap w/ qPCR	Determine the abundance of total microbial numbers and specific degraders	Elevated levels indicate presence of suitable community and ability to stimulate activity
Water Quality Parameters			
Conductivity	Field meter	Verify samples from same groundwater system	No affect on MNA evaluation
Temperature	Field meter	Verify samples from same groundwater system	No affect on MNA evaluation

Note:

1) Adapted from U.S. EPA, 1998 and Wiedemeier et al., 1999.

8.3 Data Analysis Methods

Analysis of data collected during the groundwater monitoring program will be used to support the lines of evidence approach that is standard to MNA evaluations, as noted in Section 1.

8.3.1 Demonstration of the First Line of Evidence

Plume stability will be evaluated using Mann-Kendall statistical analysis at each well. Temporal and spatial trends will be established using concentration vs. time and distance plots for each hydrogeologic unit. These data will then be used to support evaluations of mass flux.

8.3.2 Demonstration of the Second Line of Evidence

The concentration and distribution of geochemical parameters will be evaluated to demonstrate the second line of evidence for MNA. Point attenuation rates and bulk attenuation rates will be calculated from concentration vs. time and distance plots. These calculations will be used to support predictions of cleanup time (using point attenuation rates) and to predict the concentration of COCs at the discharge point to the river (using bulk attenuation rates).

8.3.3 Demonstration of the Third Line of Evidence

Elevated levels of the total microbial population and specific degrading organisms in the source areas and the plume cores could be used to demonstrate that conditions are suitable to support long-term attenuation.

9.0 REFERENCES

- AFCEE, 1995. *Technical protocol for implementing intrinsic remediation with long-term monitoring for natural attenuation of fuel contamination dissolved in groundwater*, Air Force Center for Environmental Excellence, Wiedemeier et al., 1995.
- Aziz, C.E., C.J. Newell, J.R. Gonzales, P.E. Haas, T.P. Clement, and Y. Sun, 2000. BIOCHLOR Natural Attenuation Decision Support System, User's Manual Version 1.1, United States Environmental Protection Agency, Office of Research and Development, EPA/600/R-00/008, www.epa.gov/ada/csmos/models.html.
- Christ, J.A., C.A. Ramsburg, L.M. Abriola, K.D. Pennell, and F.E. Loeffler, 2005. "Coupling aggressive mass removal with microbial reductive dechlorination for remediation of DNAPL source zones: A review and assessment," *Environmental Health Perspectives*, 113(4): 465-477.
- GSI, 2005. Mass Flux Estimates, Sauget Area 1, Sauget and Cahokia, Illinois: Groundwater Services, Inc., November 15, 2005.

- GSI, 2008. Regional Groundwater Flow and Contaminant Transport Model, American Bottoms Aquifer: GSI Environmental Inc., April 14, 2008.
- GSI, 2009a. Benzene Plume Capture by the GMCS, Sauget Area 2, Sauget, Illinois: GSI Environmental Inc., May 30, 2009.
- GSI, 2009b. Remedial Investigation Report, Sauget Area 1, Sauget, Illinois: GSI Environmental Inc., September 30, 2009.
- GSI, 2009c. Time to Clean Estimates for Chlorobenzene and 1,4-Dichlorobenzene, Sauget Area 1, Sauget, Illinois: GSI Environmental Inc., October 9, 2009.
- Heidrich, S., H. Weiss, and A. Kaschl, 2004. "Attenuation reactions in a multiple contaminated aquifer in Bitterfeld (Germany)," *Environmental Pollution*, 129:277-288.
- Kaschl, A., C. Vogt, S. Uhlig, I. Nijenhuis, H. Weiss, M. Kästner, and H.H. Richnow, 2005. "Isotopic Fractionation Indicates Anaerobic Monochlorobenzene Biodegradation," *Environmental Toxicology and Chemistry*, 24(6), 1315-1324.
- Loeffler, F.E., and E.A. Edwards, 2006. "Harnessing microbial activities for environmental cleanup," *Current Opinion in Biotechnology*, 17(3): 274-284.
- Middeldorp, P.J.M., J. de Wolf, A.J.B. Zehnder, and G. Schraa, 1997. "Enrichment and Properties of a 1,2,4-Trichlorobenzene-Dechlorinating Methanogenic Microbial Consortium," *Applied and Environmental Microbiology*, 63(4):1225-1229.
- Newell, C.J., H.S. Rifai, J.T. Wilson, J.A. Connor, J.A. Aziz, M.P. Suarez, 2002. *Calculation and Use of First-Order Rate Constants for Monitored Natural Attenuation Studies*. United States Environmental Protection Agency, National Risk Management Research Laboratory, EPA/540/S-02/500, November 2002.
- Nielsen, P.H., and T.H. Christensen, 1994. "Variability of biological degradation of aromatic hydrocarbons in an aerobic aquifer determined by laboratory batch experiments," *Journal of Contaminant Hydrology*, 15:305-320.
- Nowak, J., N.H. Kirsch, W. Hegemann, and H.J. Stan, 1996. "Total reductive dechlorination of chlorobenzenes to benzene by a methanogenic mixed culture enriched from Saale river sediment," *Applied Microbiology and Biotechnology*, 45(5):700-709.
- Ramanand K., M.T. Balba, and J. Duffy, 1993. "Reductive dehalogenation of chlorinated benzenes and toluenes under methanogenic conditions," *Applied and Environmental Microbiology*, 59(12):3266-3272.

- Reineke, W. and H.J. Knackmuss, 1988. "Microbial Degradation of Haloaromatics," *Annual Review of Microbiology*, 42:263-287.
- Sims, J.L., J.M. Sulfit, and H.H. Russell, 1991. *Reductive Dehalogenation of Organic Contaminants in Soils and Groundwater*. United States Environmental Protection Agency, Office of Research and Development, Washington DC, EPA/540/4-90/054, January 1991.
- Truex, M.J., C.J. Newell, B.B. Looney, and K.M. Vangelas, 2006. *Scenarios Evaluation Tool for Chlorinated Solvent MNA: A Research Study of the Monitored Natural Attenuation/Enhanced Attenuation for Chlorinated Solvents Technology Alternative Project*. Washington Savannah River Company, United States Department of Energy, WSRC-STI-2006-00096, August 2006.
- U.S. EPA, 1998. *Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Ground Water*. United States Environmental Protection Agency, Office of Research and Development, Washington DC, EPA/600/R-98/128, September 1998.
- U.S. EPA, 1999. *Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank Sites*. United States Environmental Protection Agency, Office of Solid Waste and Emergency Response, OSWER Directive 9200.4-17P, April 1999 (draft issued December 1997).
- U.S. EPA, 2004. *Performance Monitoring of MNA Remedies for VOCs in Ground Water*. United States Environmental Protection Agency, National Risk Management Research Laboratory, Office of Research and Development, Washington DC, EPA/600/R-04/027, April 2004.
- van der Meer, J.R., C. Werlen, S.F. Nishino, and J.C. Spain, 1998. "Evolution of a Pathway for Chlorobenzene Metabolism Leads to Natural Attenuation in Contaminated Groundwater," *Applied and Environmental Microbiology*, 64(11):4185-4193.
- van der Meer, J.R., A.R.W. Van Neerven, E.J. De Vries, W.M. De Vos, and A.J.B. Zehnder, 1991. "Cloning and Characterization of Plasmid-Encoded Genes for the Degradation of 1,2-Dichloro-, 1,4-Dichloro-, and 1,2,4-Trichlorobenzene of *Pseudomonas* sp. Strain P51," *Applied and Environmental Microbiology*, 173(1):6-15.
- Wiedemeier, T.H., H.S. Rifai, C.J. Newell, and J.W. Wilson, 1999. *Natural Attenuation of Fuels and Chlorinated Solvents in the Subsurface*, John Wiley & Sons, New York.
- Yaws, C.L., 1999. *Chemical Properties Handbook*, McGraw-Hill, New York.

EVALUATION OF MONITORED NATURAL ATTENUATION
Sauget Area 1, Sauget and Cahokia, Illinois

FIGURES AND TABLE

Table 1: Geochemical Data for Wells at and Downgradient of Sauget Area 1

The following figures are from the Sauget Area 2 RI report (URS, 2009)

Figure 4-40a: Groundwater Sampling/Gauging Locations – SHU

Figure 4-40b: Groundwater Sampling/Gauging Locations – MHU

Figure 4-40c: Groundwater Sampling/Gauging Locations – DHU

Figure 8-5: Chloride, Methane, Sulfate Isoconcentration Map – DHU

The following figure is from the Sauget Area 1 RI/FS report (GSI, 2012b)

Figure 13-1: Conceptual Monitoring Well Locations, Sauget Area 1

TABLE 1
 Geochemical Data for Evaluation of Monitored Natural Attenuation
 Sauget Area 1, Sauget and Cahokia, Illinois

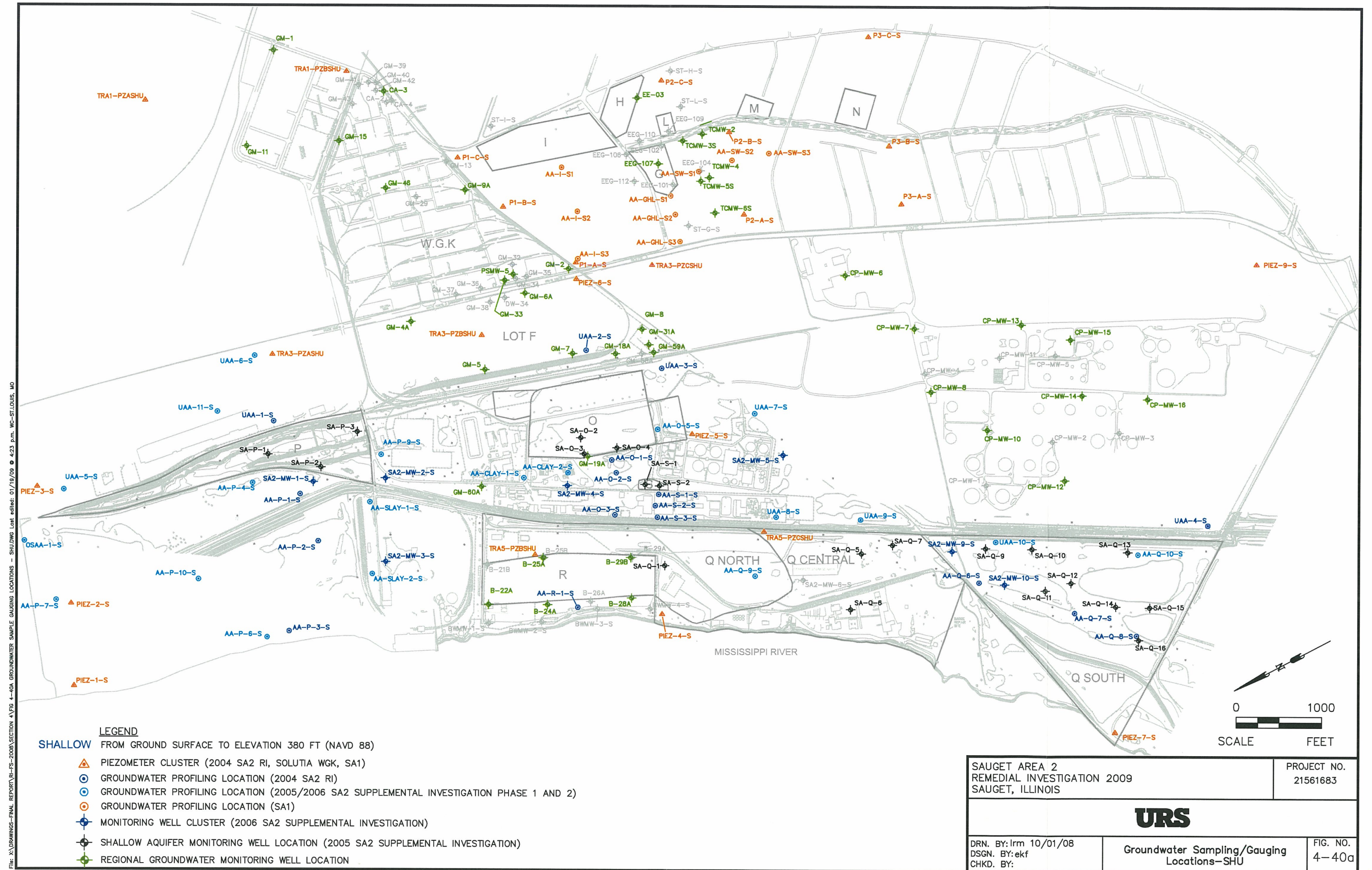
Site	Depth	Sample ID	Sample Date	Dissolved Oxygen (mg/l)	ORP (mV)	Methane (ug/l)	Sulfate as SO ₄ (mg/l)	Carbon Dioxide (mg/l)	Ethane (ug/l)	Ethene (ug/l)
SAUGET AREA 1	SHU	EE-03	8/12/05	0.65	-18	--	240	170	--	--
SAUGET AREA 1	SHU	EEG-107	7/27/05	0.82	-84	5400	160	440	17	8.8
WGK SOLUTIA - LOT F	SHU	GM-18A	7/21/05	4.44	124	0.29	48	15	ND	ND
WGK SOLUTIA - LOT F	SHU	GM-18A-D	7/21/05	--	--	--	48	49	--	--
WGK SOLUTIA - LOT F	SHU	GM-31A	8/1/05	1.549	111	5	51	78	ND	ND
SAUGET AREA 1	SHU	TCMW-2	6/28/05	--	--	68	29	16	ND	ND
SAUGET AREA 1	SHU	TCMW-3S	6/30/05	--	--	5.4	43	27	ND	ND
SAUGET AREA 1	SHU	TCMW-4	6/28/05	--	--	3.7	46	84	ND	ND
SAUGET AREA 1	SHU	TCMW-5S	6/28/05	--	--	ND	33	110	ND	ND
SAUGET AREA 1	SHU	TCMW-6S	6/29/05	--	--	0.23	41	57	ND	ND
SAUGET AREA 1	MHU	EE-01	7/29/05	0.37	3	1100	390	200	1.5	1.5
SAUGET AREA 1	MHU	EE-01-D	7/29/05	--	--	--	400	260	--	--
WGK SOLUTIA - LOT F	MHU	GM-31B	8/1/05	1.591	-76	640	260	110	--	--
WGK SOLUTIA - LOT F	MHU	GM-31B-D	8/1/05	--	--	--	270	110	--	--
SAUGET AREA 1	MHU	IMW-1S	8/2/05	1.26	98	2800	<5	73	--	--
SAUGET AREA 1	MHU	IMW-1S-D	8/2/05	--	--	--	<5	77	--	--
SAUGET AREA 1	MHU	TCMW-1M	6/29/05	--	--	22	66	94	--	--
SAUGET AREA 1	MHU	TCMW-1S	6/29/05	--	--	0.19	43	33	--	--
SAUGET AREA 1	MHU	TCMW-3M	6/30/05	--	--	62	19	63	--	--
SAUGET AREA 1	MHU	TCMW-5M	6/28/05	--	--	78	15	90	--	--
SAUGET AREA 1	MHU	TCMW-6M	6/29/05	--	--	19	26	45	--	--
WGK SOLUTIA - LOT F	DHU	GM-18B	7/21/05	0.21	-133	790	61	15	--	ND
WGK SOLUTIA - LOT F	DHU	GM-31C	8/2/05	6.564	-108	150	41	81	15	ND
SAUGET AREA 1	DHU	IMW-1D	7/28/05	0.37	-7	160	<5	56	ND	ND
SAUGET AREA 1	DHU	IMW-1I	7/28/05	0.33	10	150	<5	33	ND	ND
SAUGET AREA 1	Bedrock	BR-G	8/18/05	--	--	--	39	120 B	--	--
SAUGET AREA 1	Bedrock	BR-H	8/3/05	--	--	--	1400	64	--	--

Note: Analytical results are from groundwater sampling and testing program performed by URS in 2005 and are presented in the Sauget Area 2 RI report.

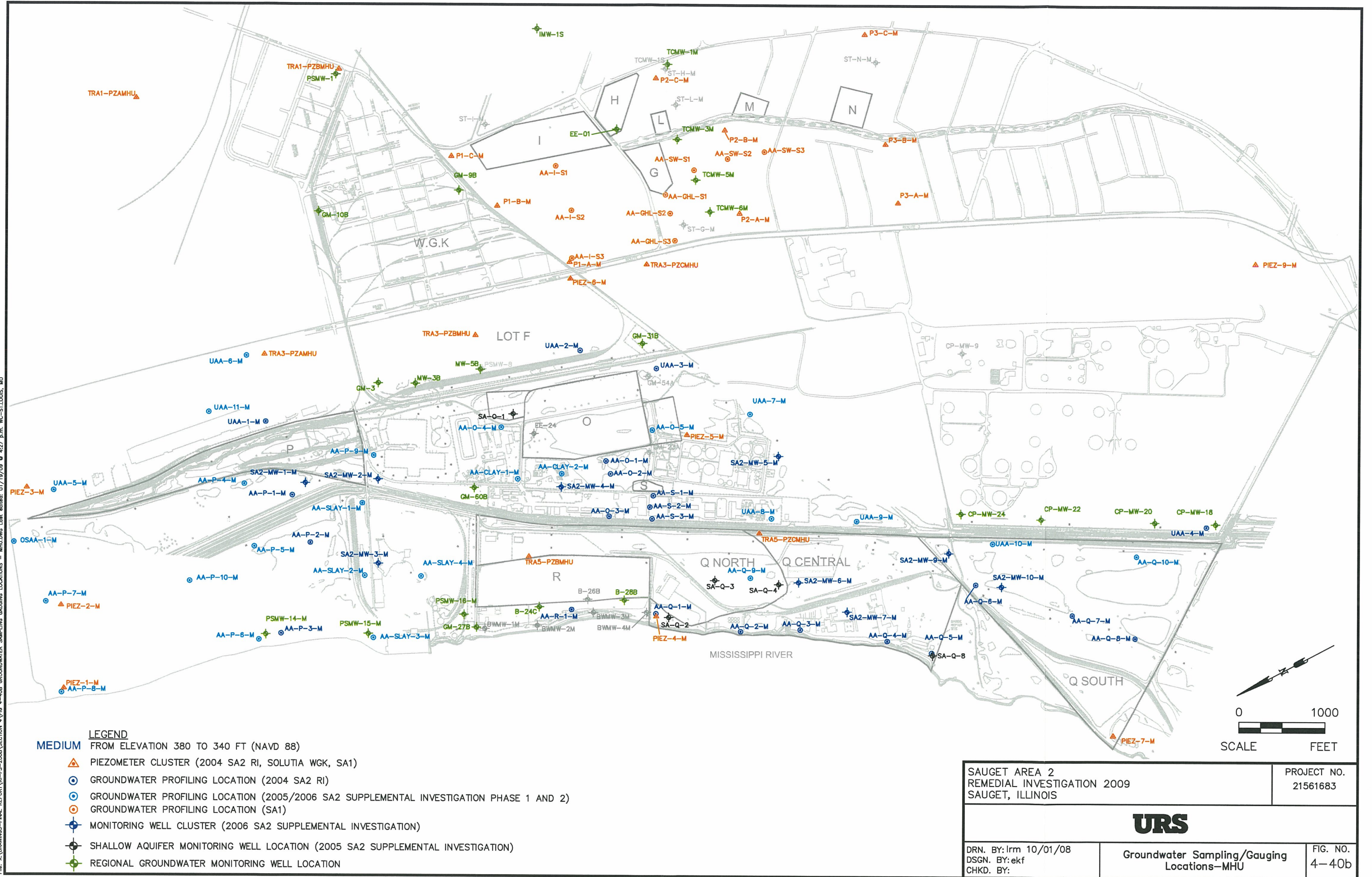
TABLE 1
 Geochemical Data for Evaluation of Monitored Natural Attenuation
 Sauget Area 1, Sauget and Cahokia, Illinois

Site	Depth	Sample ID	Sample Date	Chloride (mg/l)	Total Organic Carbon (mg/l)	Nitrogen, Nitrate (mg/l)	Nitrogen, Nitrate Nitrite (mg/l)	Nitrogen, Nitrite (mg/l)	Manganese (mg/l)	Alkalinity (mg/l)	Total Alkalinity (mg/l)
SAUGET AREA 1	SHU	EE-03	8/12/05	77	10	<0.05	<0.05	<0.05	1.3	820 B	--
SAUGET AREA 1	SHU	EEG-107	7/27/05	250	780	<0.05	<0.05	<0.05	4.1	620	--
WGK SOLUTIA - LOT F	SHU	GM-18A	7/21/05	3	0.97 J	2.8	2.8	<0.25	0.56	410	--
WGK SOLUTIA - LOT F	SHU	GM-18A-D	7/21/05	3	0.94 J	2.8	2.8	<0.25	--	410	--
WGK SOLUTIA - LOT F	SHU	GM-31A	8/1/05	8.6	3.5	0.78	0.84	0.055	1.9	430	--
SAUGET AREA 1	SHU	TCMW-2	6/28/05	61	3.7	<0.05	--	--	0.52	240	--
SAUGET AREA 1	SHU	TCMW-3S	6/30/05	56	2.5	0.05	--	--	0.85	230	--
SAUGET AREA 1	SHU	TCMW-4	6/28/05	11	2	<0.05	--	--	0.55	420	--
SAUGET AREA 1	SHU	TCMW-5S	6/28/05	3.4	1.1	0.8	--	--	0.023	490	--
SAUGET AREA 1	SHU	TCMW-6S	6/29/05	25	0.98 J	0.038 J	--	--	0.22	380	--
SAUGET AREA 1	MHU	EE-01	7/29/05	350	40	0.048 J	0.048 J	<0.05	1.8	430	--
SAUGET AREA 1	MHU	EE-01-D	7/29/05	350	41	0.065	0.065	<0.05	--	430	--
WGK SOLUTIA - LOT F	MHU	GM-31B	8/1/05	160	6.4	0.037 J	0.037 J	<0.05	2.7	710	--
WGK SOLUTIA - LOT F	MHU	GM-31B-D	8/1/05	160	6.3	0.053	0.053	<0.05	--	710	--
SAUGET AREA 1	MHU	IMW-1S	8/2/05	11	17	0.087	0.087	<0.05	0.71	460	--
SAUGET AREA 1	MHU	IMW-1S-D	8/2/05	11	18	0.035 J	0.035 J	<0.05	--	460	--
SAUGET AREA 1	MHU	TCMW-1M	6/29/05	35	1.6	<0.05	--	--	1	460	--
SAUGET AREA 1	MHU	TCMW-1S	6/29/05	110	1.3	1.8	--	--	0.15	350	--
SAUGET AREA 1	MHU	TCMW-3M	6/30/05	410	1.7	0.051	--	--	1.2	340	--
SAUGET AREA 1	MHU	TCMW-5M	6/28/05	120	1.9	<0.05	--	--	1.1	400	--
SAUGET AREA 1	MHU	TCMW-6M	6/29/05	21	0.91 J	<0.05	--	--	1	350	--
WGK SOLUTIA - LOT F	DHU	GM-18B	7/21/05	190	5.6	<0.05	<0.05	<0.05	0.54	620	--
WGK SOLUTIA - LOT F	DHU	GM-31C	8/2/05	97	9.1	0.039 J	0.039 J	<0.05	0.62	580	--
SAUGET AREA 1	DHU	IMW-1D	7/28/05	55	2.2	0.047 J	0.047 J	<0.05	0.33	490	--
SAUGET AREA 1	DHU	IMW-1I	7/28/05	50	4.8	0.046 J	0.046 J	<0.05	0.16	610	--
SAUGET AREA 1	Bedrock	BR-G	8/18/05	360	19	0.031 J	0.031 J	<0.05	--	570	--
SAUGET AREA 1	Bedrock	BR-H	8/3/05	34	1.1	0.044 J	0.044 J	<0.05	--	260	--

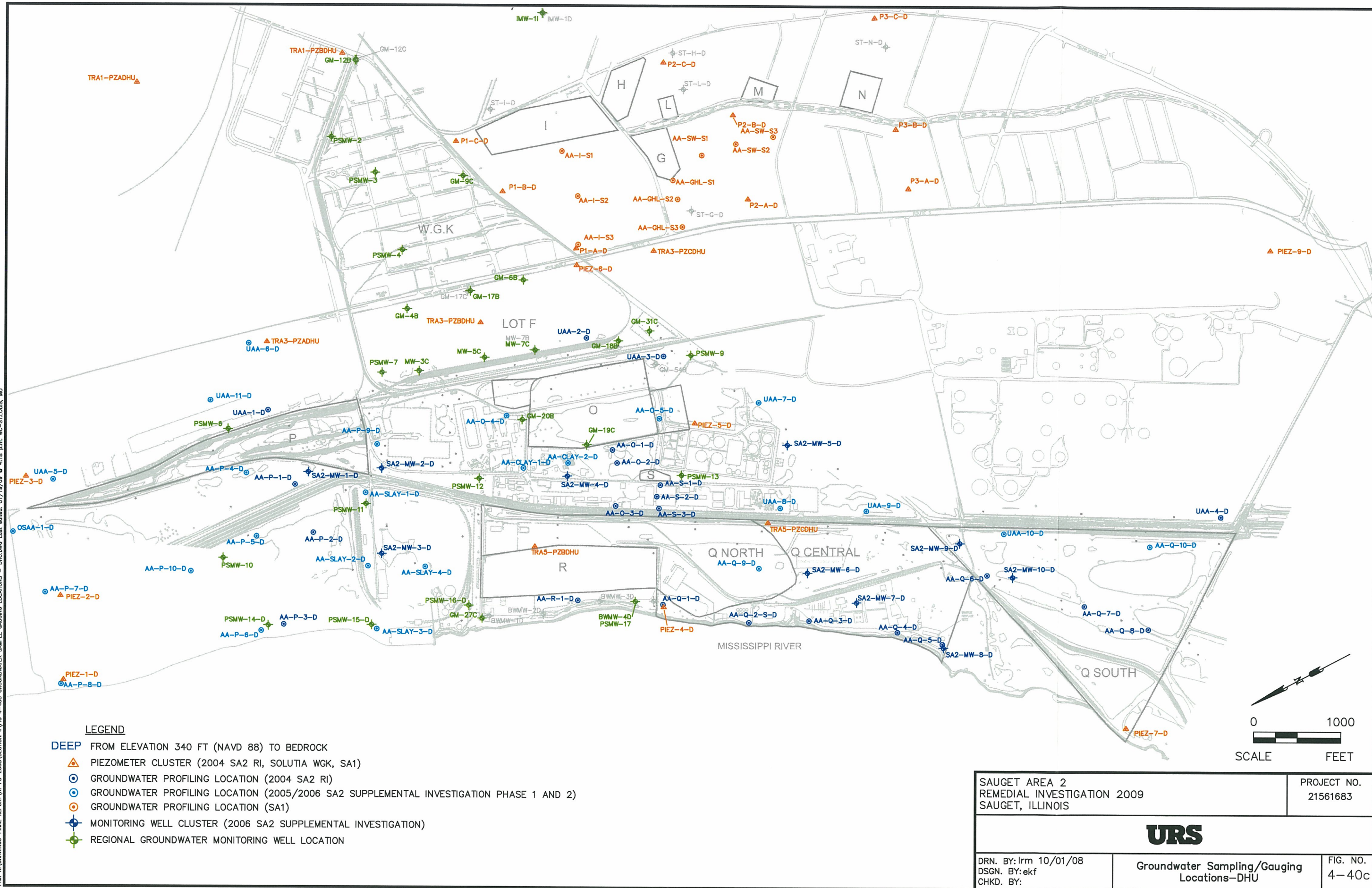
Note: Analytical results are from groundwater sampling and testing program performed by URS in 2005 and are presented in the Sauget Area 2 RI report.



File: X:\DRAWINGS-FINAL REPORT\RI-PS-2008\SECTION 4\Fig 4-40B GROUNDWATER SAMPLING GAUGING LOCATIONS - MHU.DWG Last edited: 01/19/09 @ 4:27 p.m. WC-STLOUIS, MO

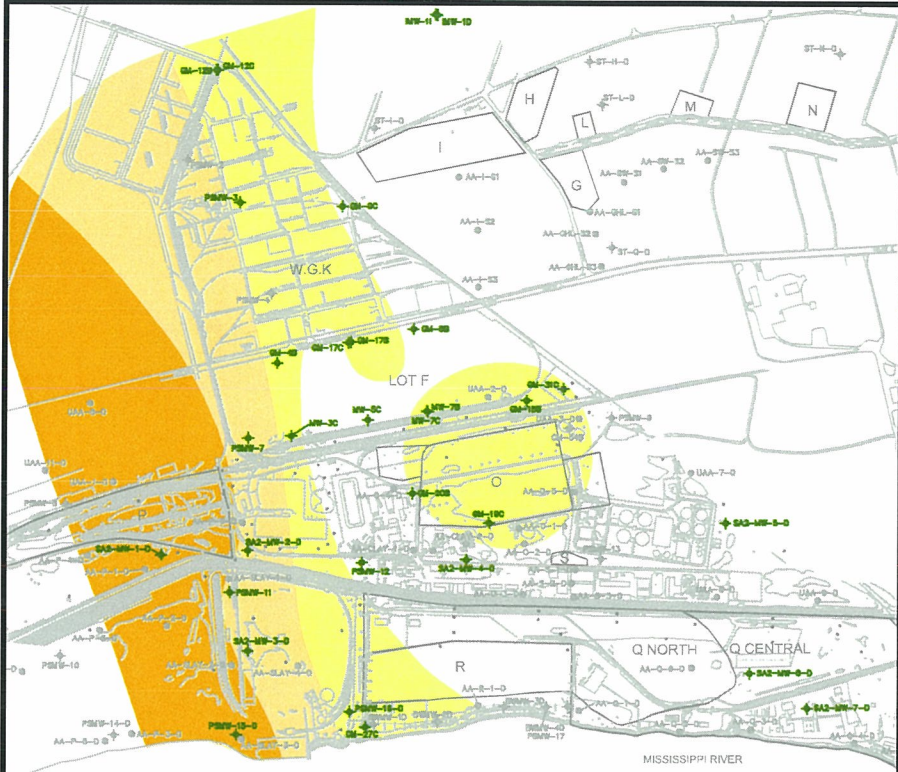


File: X:\DRAWINGS-FINAL REPORT\RI-FS-2008\SECTION A\FIG 4-40C GROUNDWATER SAMPLE GAUGING LOCATIONS - DHU.DWG Last edited: 01/19/09 @ 4:18 p.m. WC-ST. LOUIS, MO



File: X:\DRAWINGS-FINAL REPORT(RI-FS-2009)SECTION B-5 CHLORIDE-METHANE-SULFATE ISOCONCENTRATION MAP - DHU.DWG Last edited: 01/23/09 © 09-10 a.m. WC-ST. LOUIS, MO

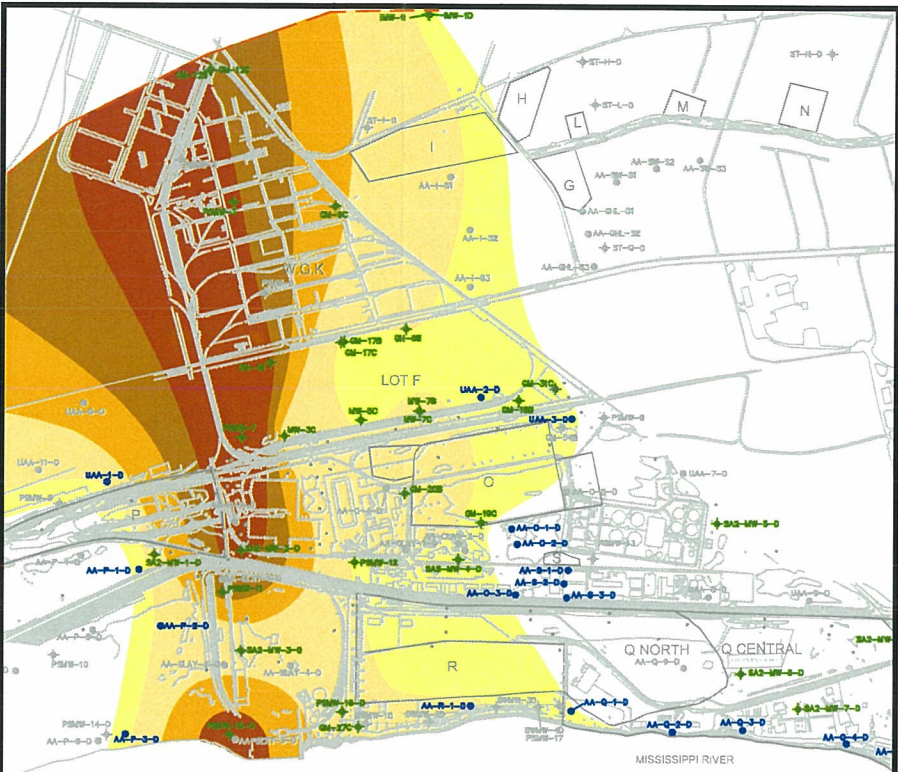
CHLORIDE



CONTOUR LEGEND

- 100 - 199 ppm
- 200 - 299 ppm
- ≥300 ppm

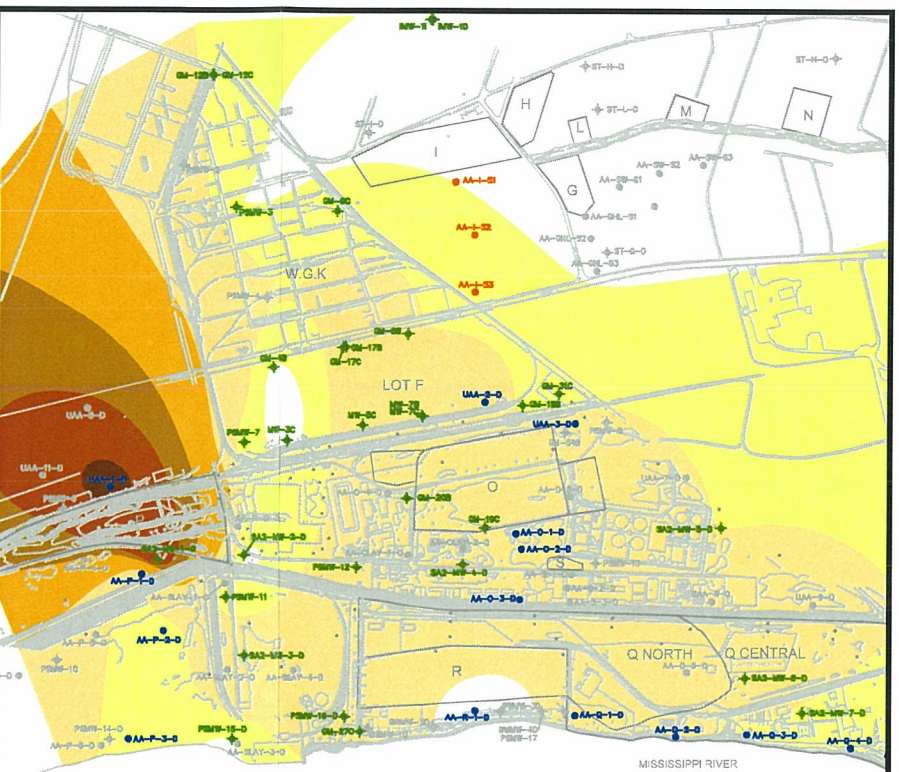
METHANE



CONTOUR LEGEND

- 100 - 999 ppm
- 1,000 - 4,999 ppm
- 5,000 - 9,999 ppm
- 10,000 - 14,999 ppm
- ≥15,000 ppm

SULFATE



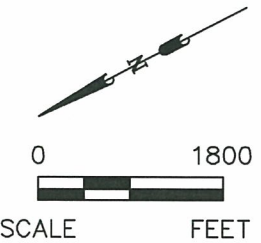
CONTOUR LEGEND

- 10 - 99 ppb
- 100 - 499 ppb
- 500 - 999 ppb
- 1,000 - 1,499 ppb
- 1,500 - 1,999 ppb
- >2,000 ppb

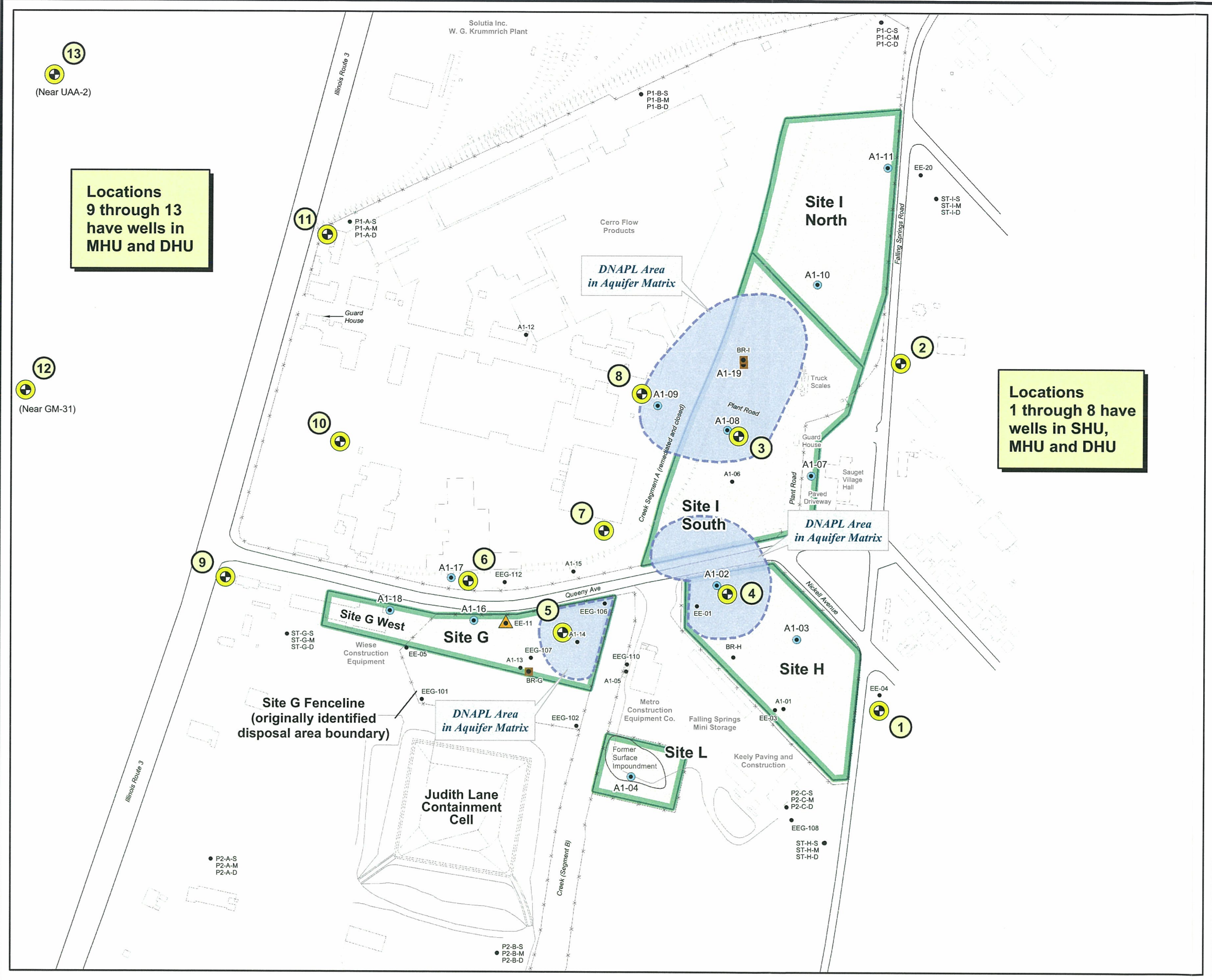
LEGEND

- DEEP FROM ELEVATION 340 FT (NAVD 88) TO BEDROCK
- PIEZOMETER CLUSTER (2004 SA2 RI)
- GROUNDWATER PROFILING LOCATION (2004 SA2 RI)
- GROUNDWATER PROFILING LOCATION (SA1)
- MONITORING WELL LOCATIONS

NOTE:
1) LOCATIONS THAT ARE GREY SCALED ARE LOCATED WITHIN THIS HYDROLOGIC UNIT, BUT WERE NOT SAMPLED.

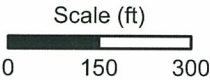


SAUGET AREA 2 REMEDIAL INVESTIGATION 2009 SAUGET, ILLINOIS		PROJECT NO. 21561683
DRN. BY: lrm 10/01/08 DSGN. BY: ekf CHKD. BY:		FIG. NO. 8-5
URS Chloride, Methane, Sulfate Isoconcentration Map - DHU		



LEGEND

- Conceptual locations for monitoring wells
- Existing monitoring well or piezometer
- LNAPL or evidence of LNAPL was found during 2005 survey
- DNAPL or evidence of DNAPL was found during 2005 survey
- No evidence of LNAPL or DNAPL was found during 2005 survey.
- Areas of DNAPL residual in the aquifer matrix



Notes:

- SHU = Shallow Hydrogeologic Unit.
MHU = Middle Hydrogeologic Unit.
DHU = Deep Hydrogeologic Unit.
- Locations 3, 4, 5, and 8 are located near existing wells A1-08, A1-02, A1-14, and A1-09, respectively. Each of these existing wells has a 15-ft screen positioned above and below the bedrock surface. These wells could potentially be used as the DHU monitoring wells for the proposed well clusters at locations 3, 4, 5, and 8.
- Locations 1 and 6 are located near existing wells EE-04 and A1-17, respectively. These existing wells are screened in the SHU and could potentially be used as the SHU monitoring wells for the proposed well clusters at locations 1 and 6.



CONCEPTUAL MONITORING WELL LOCATIONS

Sauget Area 1 Remedial Investigation/Feasibility Study
Sauget and Cahokia, Illinois

GSI Job No.	G-3450	Drawn By:	CDM
Map ID:	001_02	Chk'd By:	JAK
Issued:	25-May-12	Aprv'd:	
Scale:	As Shown	Figure 13-1	